Fundamentals of Switched Reluctance Motor Drives

Pros and Cons

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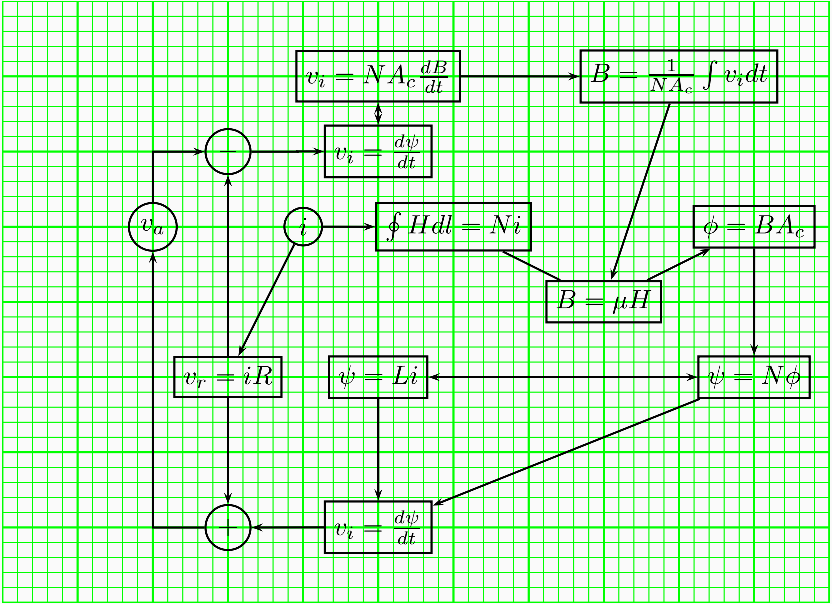
What is reluctance?



Why is reluctance?

In a magnetic circuit (where flux goes around a closed path), the excitation is provided by MMF $= Ni$

$$\Theta = Ni$$

the result of applying the mmf is the flux ϕ. The reluctance is a the resistance to the flow of the flux by the magnetic circuit.

Ohm's law analogy of magnetic circuit

$$\mathcal{R} = \frac{\Theta}{\phi} = \frac{Ni}{\phi} \tag{1}$$

If a magnetic circuit has a mean length of l_m and a a cross section area of A_c, then

$$\mathcal{R} = \frac{l_m}{\mu A_c}$$

If the magnetic circuit has an air gap, then the total reluctance is

$$\mathcal{R}_T = \mathcal{R}_{ag} + \mathcal{R}_m$$

$$\mathcal{R}_T = \frac{l_{ag}}{\mu_0 A_c} + \frac{l_m}{\mu_o \mu_r A_c}$$

Reluctance, Inductance and flux linkage

The inductance of the magnetic system is given as

$$L = \frac{\psi}{i} = \frac{N\phi}{i}$$

Since

$$\phi = \frac{\Theta}{\mathcal{R}}$$

, we get

$$L = \frac{N\Theta}{\mathcal{R}i} = \frac{N^2}{\mathcal{R}}$$

When there is flux created, energy gets stored in the magnetic field

$$W_{field} = \frac{1}{2}BHV = \frac{1}{2}Li^2 = \frac{1}{2}\psi i$$

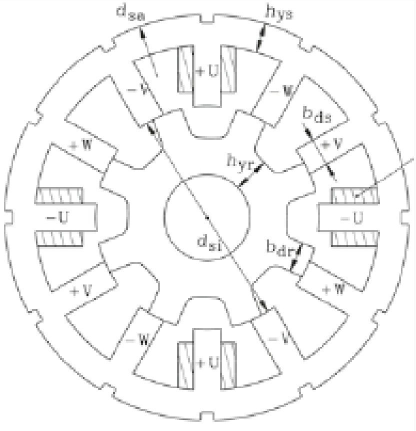
We can get torque using energy balance equation

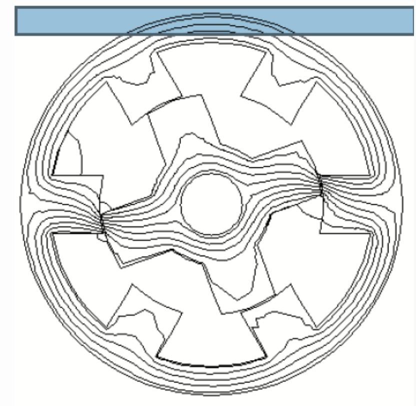
$$dW_{elec} = dW_{field} + dW_{loss} + dW_{mech}$$

Where

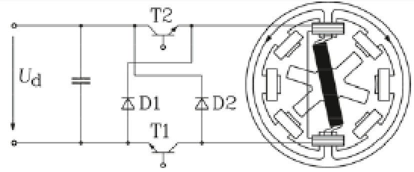
$$dW_{mech} = m_e \omega dt$$

Working principle of reluctance machine

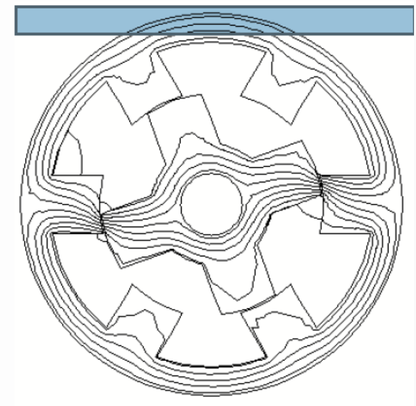




The torque on the rotor moves it into minimum reluctance position



- Turn off the coil once it aligns with stator poles
- Turn on the next coil for the next pole alignment
- Only one phase is active at any given time



Torque production in SRM i

The electrical power given to the coil is used in

$$P_e = P_{loss} + \frac{dW_{field}}{dt} + P_m \tag{2}$$

where P_{loss} is lost in the coils, and P_m is the mechanical power given to the torque.

The magnetic energy in every phase winding and its change due to coil current and rotor position is given as

$$W_{field} = \frac{L(\gamma_m)I^2}{2} \Rightarrow \frac{dW_{field}}{dt} = iL\frac{dI}{dt} + \frac{1}{2}I^2\frac{dL}{d\gamma_m}\Omega_m \tag{3}$$

The coil voltage can be written using Faraday's law as

$$V = RI + \frac{d\psi}{dt} = RI + L\frac{dI}{dt} + I\frac{dL}{d\gamma_m}\Omega_m \tag{4}$$

We can calculate power as

$$P_e = V \cdot I = RI^2 + IL\frac{dI}{dt} + I^2\frac{dL}{\gamma_m}\Omega_m \tag{5}$$

Equating 5 and 2 using 3 We can calculate

Torque production in SRM ii

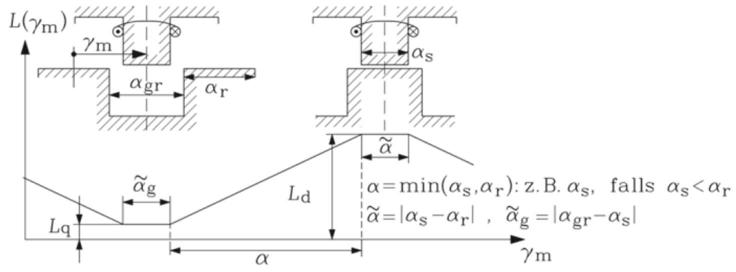
Torque in SRM

$$P_m = \frac{1}{2} I^2 \frac{dL}{d\gamma_m} \Omega_m \tag{6}$$

and since

$$M_e = \frac{P_m}{\Omega_m} = \frac{1}{2} I^2 \frac{dL}{d\gamma_m} \tag{7}$$

Variation of Inductance and Torque: Ideal condition

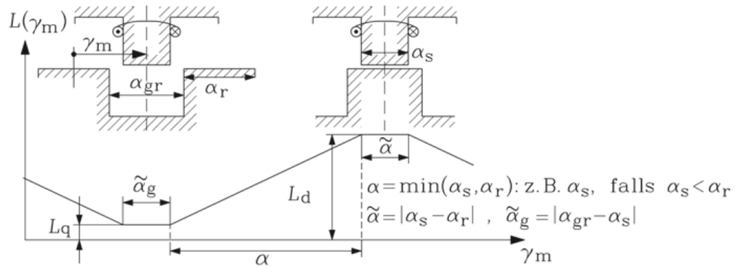


Assuming that the inductance varies linearly with rotor position, the torque due to phsae 1 is given as

$$M_e, 1 = \frac{1}{2} I^2 \frac{dL}{d\gamma_m} = \frac{1}{2} I^2 \frac{L_d - L_q}{\alpha}$$

where α is the angular duration when inductance increases

Motor and Generation operation



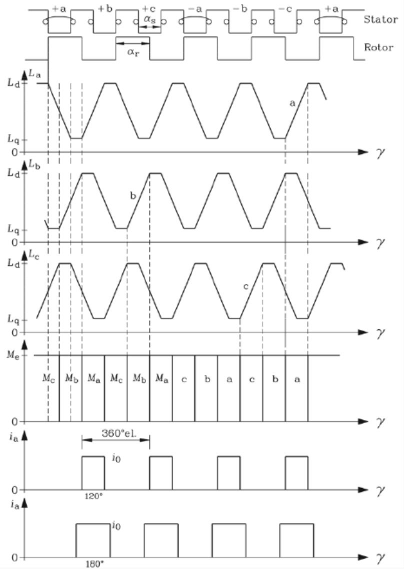
Depending on when the coil is excited, we get motoring of generation operation

$$M_e, 1 = \frac{1}{2} I^2 \frac{L_d - L_q}{\alpha} > 0$$

$$M_e, 1 = \frac{1}{2} I^2 \frac{L_q - L_d}{\alpha} < 0$$

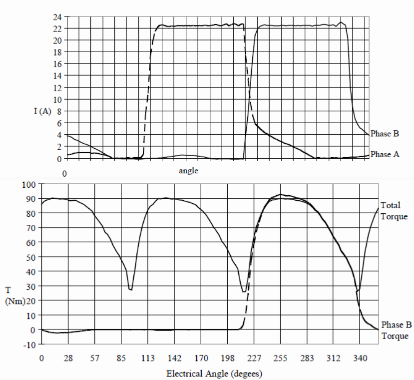
The torque is zero when the stator and rotor poles are aligned. You need to switch of the current in phase 1 and switch on the next phase

SRM Torque due to phases



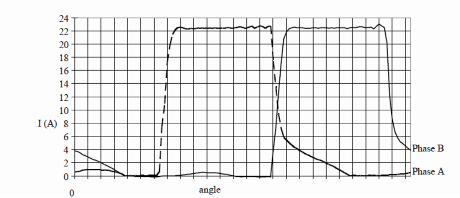
- Each phase is switched sequentially
- Rotor position information is needed for switching
- in practice perfect square wave current is not possible
- Hence there will be net torque ripple

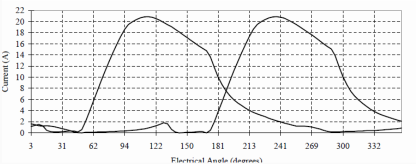
SRM Torque in practice



- Rate of current rise depends on inductance and $\frac{dL}{d\gamma_m}$
- At low speeds the like 200 rpm the current is fairly square
- Actual torque shows a large ripple

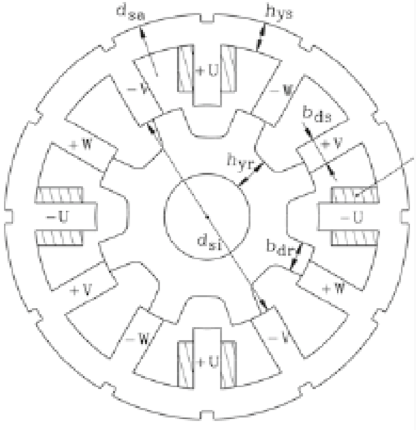
SRM Torque in practice





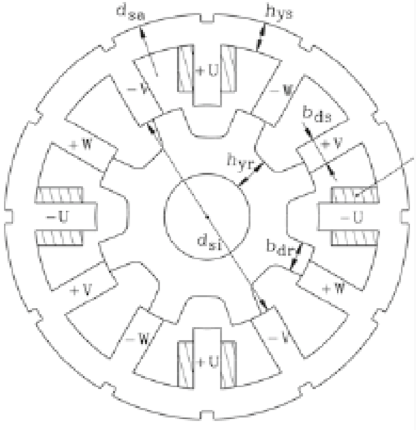
- Current shape is lost at higher speeds
- The torque ripple increases with speed
- It also produces a lot of vibrational noise as the stator is pulled in during the alignment

SRM Structures



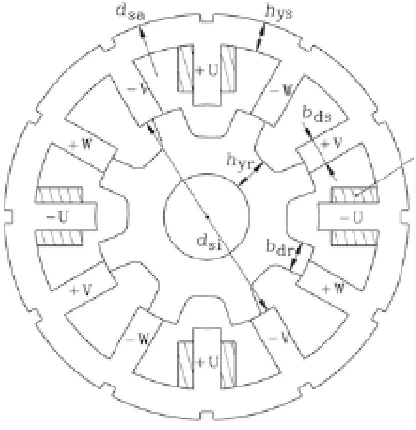
- For three phase the stator to rotor poles that can be used are
- 6:4, 12:8, 24:22 (Stator poles > rotor poles)
- for 4 phases 8:6 can be used
- SRM always needs a power converter
- Hence it can supply any number of stator phases

SRM so called advantages



- No magnet needed
- High torque density
- Only one winding (as compared to Induction Motor)
- cheap to manufacture

SRM Disadvantages



- Requires power converters to run (not really a disadvantage)
- High Torque ripple
- High noise at high speeds
- Not really cheap when compared to total cost of standard drive
- Only competitive when used in large number and design is optimized for the application (e.g. washing machine)
- Came with lot of hype and promise, but has not been able to capture the Induction motor market or the PMSM market

References i

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- A. Binder(2017), Electrical Machines and Drives (*in German*), Springer